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Prospects for expanded utilization of biogas in Germany

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ABSTRACT

The prospects for expanded utilization of biogas systems in German was analysed, by identifying the operational and policy factors affecting the complete chain of processes from implementation process for biogas plants, through to biogas production and utilization. It was found that the Renewable Energies Act (EEG) and energy tax reliefs provide bases for the support of expanded utilization. Upgrading of biogas to natural gas quality for utilization in the transportation sector was arguably the most promising technology that could support rapid utilization expansion. Sustainable deployment of biogas systems in light of the unstable feedstock prices and availability, and the need for subsidy-free operation in the long term requires; enhancement of feedstock flexibility and quality characteristics to maximise gas yield, and optimisation of the anaerobic digestion process management. Assessment of energy balance and potential environmental impacts of the integrated process chain provides a holistic assessment of sustainability. The results also support the development and foster of policies and framework for development of biogas as environmentally friendly energy resource, among a mix of renewable energy sources, hence, compete favourably with fossil fuels to enhance the prospects for expanded utilization.

Contents

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1. Introduction

Germany is currently the world leader in the deployment of biogas technology. In the last decade, the number of plants increased from 370 in 1996–3891 in 2008 [1]. The electrical power supplied to the national grid from biogas plants also increased from 60 kW_{el} in 1999 to 350 kW_{el} in 2008 on average [1], mainly due to implementation of the Renewable Energy Sources Act (EEG). Under the EEG, there is payment for supply of electricity from renewable resources [2,3]. The biogas plants, with a total output of approximately 1400 MW_{el} in 2008 produce about 10 TWh electricity per annum, which accounts for about 1.6% of the total demand [4], but the technical potential is estimated to be almost 60 TWh per annum [5]. Biogas is predominantly used for Combined Heat and Power (CHP) and in electricity generation and feed-in to the national grid [6]. A scheme that allows for injection of bio-methane (enriched biogas) into the natural gas grid is also in place, which has expanded biogas utility [7]. It is estimated that, optimisation of available feedstock for decentralised plants, has potential to further enhance biogas utilization [8].

Like with any other renewable energy resources, judicious deployment of biogas technology will contribute to reduction in greenhouse gas (GHG) emissions and air pollution, due to the expected reduction of the use of fossil fuels. Fig. 1 compares GHG emissions associated with different electricity production options from a life-cycle perspective for biogas, fossil fuels, and other renewable energy sources. The calculated negative emissions for biogas-CHP are explained by the substitution of oil fuel with biogas. The underpinning anaerobic digestion (AD) process can also be used for waste management and enhancement of soil fertility through spreading of the spent feedstock—the digestate. The requisite organic feedstock are locally available and renewable, therefore, with the right policy incentives, security of energy supply could be enhanced. The deployment of biogas technology created about 10,000 jobs in Germany in 2007 [9], and contributed to economic growth with the increased export of the technology.

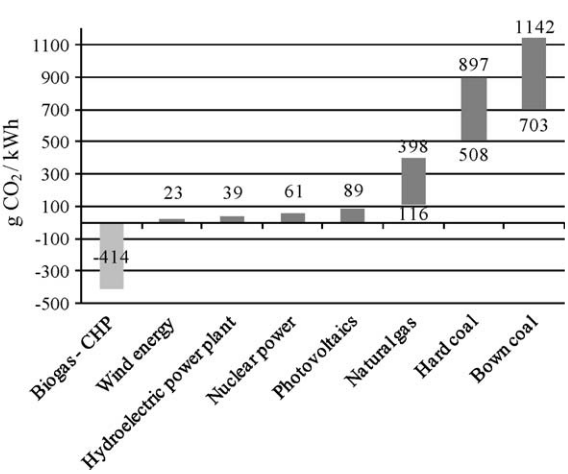

Fig. 1. Comparison of GHG emissions associated with different electricity production options from a life-cycle perspective (including upstream processes and material consumption from producing energy generation plants) [87].

However, the competitiveness of biogas plants has lately been impeded by highly variable prices of feedstock like corn, and the decreasing government subsidy. Implementation and operation of biogas plants is a complex process; it requires planning permission from the municipal or regional authorities, rigorous feedstock supply logistics, AD process control, marketing of electricity/biogas, and disposal of the digestate. Environmental awareness of the populace and environmental protection regulations also strongly influence their feasibility.

The objective of this study was to assess the prospects for expanded deployment of biogas technology in Germany, by identifying key factors affecting the complete chain of processes in plant implementation from the planning process, installation and commissioning, to feedstock supply, and biogas production and utilization. The stepwise methodology included:

(1) Description of state-of-the-art and demarcation of elements biogas systems into feedstock supply logistics, biogas production and treatment of spent feedstock—the digestate, and biogas utilization elements.
(2) Literature review to compile quantified descriptors of the elements of production system, including feedstock types, deployed biogas production technologies, biogas utilization for electricity generation and transport fuel, and sustained utilization of the digestate including safe disposal option.
(3) Economic analysis was carried out for biogas production from different feedstock, including feedstock supply considerations and handling of the digestate on basis of industry data. Evaluation of different biogas utilization pathways based on energy audit of biogas production systems was also implemented.
(4) Analysis and discussion of active policy considerations entailing the incentives and barriers to biogas production and utilization with impacts on the potential for expanded biogas utilization. These were benchmarked against three selected 'biogas-peer' countries including, Italy, Sweden and Switzerland, as an intended continuous process by which Germany will seek to challenge its technology and practice leading to sustainable utilization of biogas and therefore enhanced contribution to renewable energy resource mix.

In all cases, the data used was derived from peer-reviewed scientific literature and technical reports with relation to current practice in biogas production and utilization technology in Germany, and corroborated on the basis of working experience of the authors, and through personal communication with selected experts in Germany. The policy issues covered are therefore focused on specific areas of weakness in the integrated biogas utilization system, where technical and economically viable potential for optimisation exist. The biogas peer countries were selected on the basis of; strategy for sustainable feedstock initiatives and existing high feedstock potential from agro-industry (Switzerland, Italy) [10,11], pioneering and extensive use of bio-methane for transportation fuel (Sweden) [12,13], and high feed-in-tariffs for biogas coupled with tradable green certificates for electricity generated from renewable energy sources (Italy) [11].

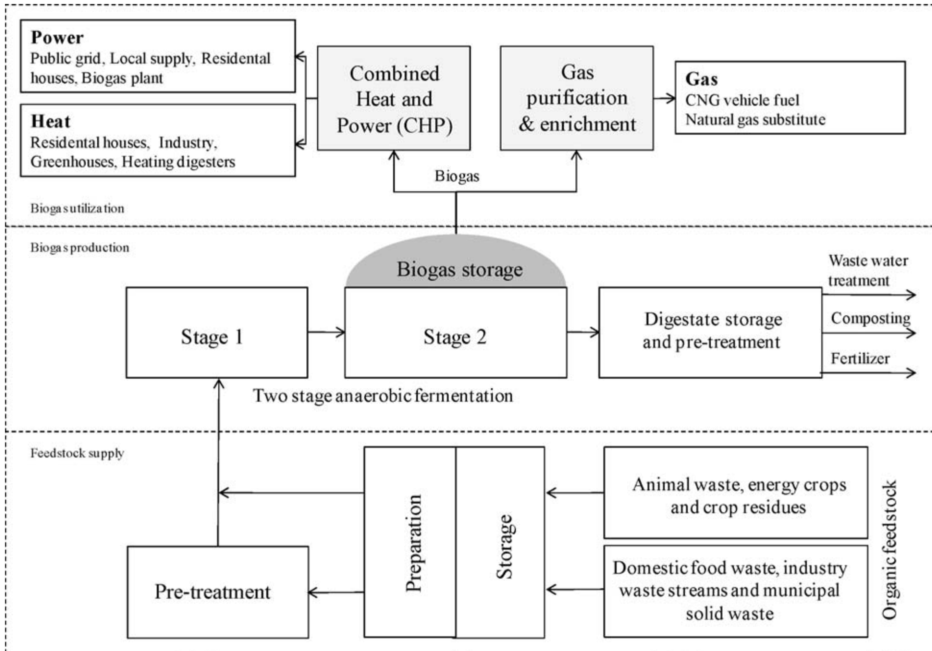

Fig. 2. Stages of biogas production systems.

2. State-of-the-art in biogas energy systems

Biogas is produced by AD of organic feedstock, the most common being; animal waste and crop residues, dedicated energy crops, domestic food waste, and Municipal Solid Waste (MSW). Integrated processes include (Fig. 2), feedstock supply and pre-treatment; AD, gas treatment and utilization, and recovery, pre-treatment and use of digestate. Biogas consists of 50–75% methane (NH_4), 25–45% carbon dioxide (CO_2), 2–7% water (H_2O) at 20–40 °C, up to 2% nitrogen (N_2), trace of oxygen (O_2), and less than 1% hydrogen (H_2) and hydrogen sulphide (H_2S) [14]. Biogas systems in Germany developed from predominantly small on-farm plants, using liquid manure and crop residue mixtures for feedstock. The introduction of incentives for increased utilization of renewable resources via the EEG led to proliferation of industrial-scale plants with elaborate logistics [15]. Such plants are organised in industrial parks and produce approximately 250 m^3/h ($\approx$1 MW) of biogas from wide range of feedstock. The German company EnviTec GmbH, is credited with developing the world biggest biogas park at Penkun, with a capacity of 20 MW_{el}.

Mechanical components of farm-scale biogas plants generally derive from agricultural equipment. For example, the animal feed screw-mixer is used to convey feedstock into the digesters. On the other hand, large-scale biogas plants handling non-standard feedstock, e.g., slaughter house wastes, use more reliable and advanced technology. Waste-disposal regulations require pre-treatment (sterilization) of some categories of waste before the AD process [16]. Wet digestion process and percolation are predominantly used [17], but dry digestion process, has also gained popularity. Biogas utilization options depend on energy demand and location of the plant; part of the generated heat may be used for heating the digester to maintain optimal conditions for AD processes, and nearby animal stalls and houses. Technology for upgrading of biogas to bio-methane for injection into the natural gas network is still under development.

The AD process reduces odours, pathogens and other components that could be harmful to plants (e.g., organic acids), and coupled with better fluidity and therefore easy spreading, the digestate's characteristics as substitute to mineral fertilizer are enhanced. GHG, including, carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4) and nitrous oxide (NO), are also reduced. For example, in 2006, a CO_2 emission reduction of 47 million tonnes was attributed to the use of biomass feedstock (including biomass and biofuels) [18]. NH_3 and NO are estimated to be up to 21 and 200 times more harmful to the environment than CO_2, respectively [19].

3. Biogas production, utilization and potentials for expansion

3.1. Production potential

The exuberance for complete replacement of fossil fuels by renewable energy resources, e.g. biomass, is not supported by maturity of the underpinning science, engineering and technology [20]. However, it is realistic that potential expansion in renewable energy utilization will depend on technology improvement and adoption of policies that enhance economics of individual components of the selected renewable energy resource mix [21]. The outcome of a comparative analysis of biogas yield and energy outputs for selected biogas-to-energy conversion pathways in feedstock co-digestion regimes done for this study is summarised in Table 1. The theoretical amount of sewage gas, landfill gas, and biogas available is about 23–24 billion m^3, with an energy potential of 417 PJ per annum, of which agricultural biogas systems account for 77–85% [5]. The overall technical potential of the installed biogas systems to the energy market is estimated to be up to 18% of installed electrical power, 20% of natural gas consumption or 35% of traffic volume with 241 billion passenger car kilometres [22]. Feedstock supply logistics is key determinant of biogas plant viability; Table 2 shows the results of economic analysis of feedstock supply and handling its digestate for different feedstock types, and Fig. 3 summarises the contribution of different feedstock categories to biogas production in Germany.

3.2. Feedstock from agricultural sector

3.2.1. Farm waste

Farm wastes, especially liquid manure, are the preferred feedstock, due to ready availability and ease of handling. They also stabilise the AD process, and contain valuable minerals and

Table 1
Biogas yield and energy outputs for different biogas-to-energy conversion pathways in feedstock co-digestion regime for small and large-scale biogas plants. The data are based on energy audit of biogas production systems in the respective scales of operation. The blank entries indicate that the respective technology was unviable for the scale of biogas operation considered.

	Energy yield by scale of biogas plant (GJ/$t_{Dry\ Matter}$)	
	Co-digestion in small-scale biogas system[a]	Co-digestion in large-scale biogas system[b]
Biogas yield (GJ/t_{DM})	8.9	16.4
(1) Combined Heat and Power (CHP)–electricity generation without heat utilization[c]	2.9	–
(2) CHP—electricity generation with heat utilization[d]	4.1	–
(3) CHP—electricity generation, heat and cooling energy utilization[e]	4.7	–
(4) Stirling engine—electricity generation and heat utilization	4.0	–
(5) Micro gas turbine—electricity generation and heat utilization	3.9	–
(6) CHP with waste heat utilization in Organic Rankine Cycle technology	3.2	–
(7) Fuel cell technology for electricity generation	–	8.3
(8) Upgrading biogas (bio-methane) for injection into gas grid	–	16.4
(9) Upgrading biogas for utilization as transportation fuel	–	16.4

[a] Co-digestion of cattle manure and corn silage (feedstock from agricultural sector).
[b] Co-digestion of predominantly industrial sector waste and Municipal Solid Waste (MSW).
[c] Approximately 50% of generated heat from CHP conversion is used for heating digesters and sterilization of feedstock, if necessary. Other 50% would be available for utilization off-site, but was not used in this case.
[d] Regarding seasonal demands, approximately 60% of available waste heat of CHP conversion is used for heat utilization off-site by transmission.
[e] Regarding seasonal demands, approximately 60% and 40% of available waste heat of CHP conversion is used for heat utilization off-site by transmission and in Combined Cooling Heating and Power unit, respectively.

Table 2
Economic analyses of biogas production for feedstock supply and handling the digestate for different feedstock types on basis of industrial data.

Feedstock supply and handling the digestate	Feedstock from agricultural sector		Feedstock from industrial sector and Municipal Solid Waste	
Activity	Cattle manure	Corn silage	Municipal Solid Waste (MSW)[a]	Food residues
Biogas yield (GJ/t_{DM})	5.9	10.8	6.6	12.7
Dry matter content of feedstock (DM)	8%	35%	40%	16%
Feedstock supply[b]				
Cultivation (€/t)	–	1.87	–	–
Pre-treatment (€/t)	–	–	8.10	3.24
Sterilization (€/t)	–	–	–	1.68
Collection (€/t)[c]	–	–	29.50	11.30
Transport (€/tkm)	0.05	0.13	0.07	0.03
Digestate handling[b]				
Degradation degree of organic dry matter	60%	80%	60%	87%
DM content of digestate	4.3%	11.1%	31.8%	4.0%
Amount of digestate (t)[d]	0.7	2.9	3.3	1.3
Loading and spreading of digestate (€/t)	0.25	1.05	1.71	0.67
Transport of digestate (€/tkm)	0.04	0.14	0.18	0.07
Transportation distance[e]	22 km	350 km	425 km	90 km

[a] Compositions of MSW is highly variable and can significantly influence biogas yield [92].
[b] Price per kWh electricity (kWh_{el}) was assumed to be €0.13, which is equal to average rate [93], price for kWh thermal energy (kWh_{th}) was assumed to be €0.07, based on current rates offered by regional gas suppliers, price per litre diesel fuel was assumed to be €1.10, which presents average pump price in Germany [94].
[c] Collection route was assumed to be 45 km for urban areas.
[d] Amount of digestate to handle, resulting from dilution or dewatering feedstock to a dry matter content of 12% for wet anaerobic digestion process.
[e] Energy balance assessed to be negative for feedstock and digestate transport exceeding respective transportation distances.

trace elements which are important for subsequent use of the digestate as fertilizer. Most biogas plants (about 95%) therefore use liquid manure for co-digestion with other feedstock [23]. Co-digestion of manure with litter, and crop residue alone, account for about 96.5 PJ and 13.7 PJ of biogas energy per annum, respectively [24]. Up to 10% increment in the use of crop residue is possible without affecting humus production on farmland [25]. Use of agricultural waste feedstock only incurs transportation cost, which counts for €0.05/tkm in case of cattle manure (Table 2), but, due to low organic dry matter content and consequently low energy density, the optimal transportation distance for liquid manure feedstock is limited to ca. 22 km (Table 2).

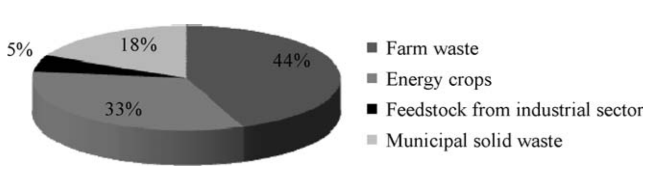

Fig. 3. Contribution to biogas potential in Germany by feedstock type.

3.2.2. *Energy crops*

Important considerations for using energy crops as feedstock by biogas plants include the availability of own land for production, gas yield potential of the crop, and feedstock transportation distance. Currently, the total area under energy crops specifically for biogas production is estimated to be 400,000 ha [26] and the biogas energy potential of the available land in the short term is estimated at 236 PJ per annum [27]. Energy crop cultivation is a cost-intensive process which leads to energy costs of €1.87/t

(Table 2). Energy crop feedstock is also purchased and is therefore exposed to fluctuations in market conditions (price, availability and logistics); e.g., a maximum economic transportation distance for corn silage which is a popular biogas feedstock is ca. 15–20 km [28]. Corn and grass silage are preferred [23]; e.g., over 80% of the biogas plants in Bavaria use corn silage feedstock. Corn silage yields up to 489 m^3 of biogas per tonne dry matter, compared to 250 m^3 for cattle manure [29]. Analysis in this study showed that the energy balance for corn silage turn negative for transportation distances exceeding 350 km (Table 2).

It is recognised that extensive production of high yield corn in monoculture has negative environmental consequences, namely: endangerment of biodiversity, use of high amount of pesticides, lowered soil fertility, and requirement for genetically modified crop varieties to enhance yield [30]. Therefore, a protocol for sustainable use as energy feedstock is required.

3.3. Feedstock from industrial sector and Municipal Solid Waste (MSW)

Feedstock from industrial sector and MSW streams is also used for biogas production. For example, useful energy potentials of wastewater treatment plants and landfills are estimated to 19.5 PJ and 18 PJ per annum, respectively [24]. Under the EEG, large-scale wastewater treatment plants are designated to feeding biomethane into the natural gas utility grid, while it supports electricity generation for small-scale plants.

The potential biogas energy production from industrial and municipal soil waste streams is estimated at 9.3 PJ and 12.5 PJ per annum, respectively, the latter benefiting from widespread pre-separation of bio-waste [7]. Although biomass feedstock like grass, leaves and woody material generated from landscape maintenance are often considered for estimations of this potential (12 PJ per annum), they contain high lignin content which impede AD [23]. Other contraries and harmful substances can also impede the digestion process. To allay this, feedstock pre-treatment and/or sterilization are required. Currently, energy inputs to pre-treatment for MSW is 60 kWh_{el}/t and for sterilization of food residues 24 kWh_{el} plus 22.4 kWh_{th}/t. These translate to energy costs of €8.10/t for MSW and €4.92/t for food residues (Table 2).

3.4. Biogas production technologies

Approximately 70% of biogas plants in Germany are based on wet digestion process [24] whereby, besides liquid manure, digesters are also fed with other organic co-feedstock [31]. Feedstock is pre-treated to accelerate the digestion process (Fig. 2), and where regulations demand, they are sterilized or harmful sediments discharged from digesters (e.g., for chicken litter) without impairing the digestion process. Technologies for pre-treatment of feedstock prior to digestion have been adapted from waste-processing industry. Mechanisms for conveying feedstock include automated screw conveyors for better control of feed-rate, while liquid feedstock is pumped into the digesters (Fig. 4). The most common digesters are made from concrete, the basic design being derivative of liquid manure storage tanks used in agriculture and water treatment plants. Two-stage AD systems are predominant, i.e., separate the hydrolysis from the other stages of methane generating processes (Figs. 2 and 4), which allows for more efficient digestion process and for safety [32].

The complexity of process engineering for the range of feedstock used is such that optimisation, in most part, is possible only in laboratory scale studies. Their adoption for full-scale operations is still afflicted with uncertainties. For example, the stirring technology for homogenous mix in the digester is yet to be optimised for the range of feedstock [33], pneumatic mixing and hydraulic agitation have been tested [23]. Biological processes in AD are slow and require close monitoring [34]. Consequently, manually controlled digesters are deemed inefficient, and plants with automatic control systems have been deployed to optimise production. Closed storage for the digestate is necessary to control odour emission [16], and secondary collection of the residual gas can enhance energy yield by up to 10% [35]. Presently, operation of majority of biogas plants is suboptimal, mostly to 80% capacity [6], which is partly attributed to lack of specialised training for technical plant operators on biological process control.

3.5. Utilization of biogas for electricity generation and vehicle fuel

In biogas conversion to electricity, Otto Cycle gas engines are most commonly used [31]. For small-scale plants taking predominantly agricultural feedstock, the estimated energy output equal to electricity for feeding into the public grid is ca. 2.9 GJ/t_{DM} (Table 1). Other conversion processes that have been used at pilot scale include; the Organic Ranking Cycle (ORC), the Stirling engine [36], the Micro gas turbine, and Fuel cells [37], for which the corresponding outputs are 3.2, 4.0, 3.9 and 8.3 GJ/t_{DM} of energy, respectively (Table 1). Electricity generation from biogas increased from 5.4 TWh in 2006 to 10 TWh in 2008, which corresponds to 1.6% of total power consumption in Germany. Heat generation by biogas plants increased from 1.0–1.4 TWh in 2006, to 3.6 TWh in 2007 which correspond to 3–4% of heat generation from renewable energies [4].

Small-scale biogas plants are mostly used for CHP in decentralised on-farm units. A survey of 177 representative biogas plants showed that, on average, 6% of their total revenue originated from heating utility [16]. However, heat transmission is accompanied by heat losses ranging between 3.5% and 20% depending on transmission distance [29]. Seasonal variations in thermal loads may be serviced with Combined Cooling Heating and Power (CCHP) units, which enhance plant efficiency by up to 15% compared to CHP for electricity generation with heat utilization (4.1 GJ/t_{DM}) (Table 1), and could also guarantee revenue for surplus generation. For large-scale biogas plants without thermal conver-

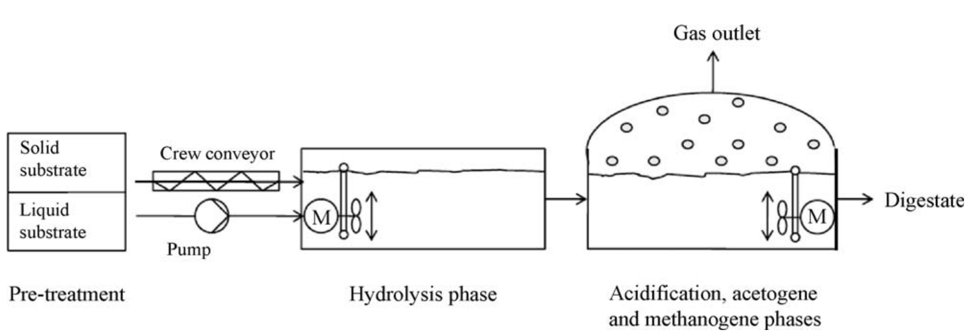

Fig. 4. Schematic of a two-stage anaerobic digestion system.

sion, biogas upgrade to bio-methane for subsequent injection into gas network is an attractive energy market option (Fig. 2) as it does not require conversion [24]. For such a system based on large-scale industrial plant model, it is estimated that 16.4 GJ/t_{DM} of energy output is achievable (Table 1). Seven plants in Germany already upgrade biogas to natural gas quality, and additional 20–30 plants are under development [38]. However, cost of the gas upgrade technology still restricts the deployment to large-scale plants [7], the breakeven plant capacity for economic grid injection being equivalent to 1–1.5 MW_{el} of electricity [17].

Utilization of biogas as transport fuel is more diffused in neighbouring countries, e.g. Switzerland [39] and Sweden [12,40] than in Germany. Although, energy yield of upgraded biogas when used as a substitute transportation fuel is nearly equal to energy value of the biogas, due to negligible conversion losses, widespread deployment has been restricted by less elaborate gas station infrastructure and high cost for implementation [7]. The investment costs in Fuel cell technology for conversion of biogas to electrical power is about four times higher [41], therefore, Fuel cells are still operated at pilot scale.

3.6. Disposal of digestate from biogas systems

Feasibility of biogas plants must consider the amount, characteristics, and the potential utilization of the digestate [34]. The current output of digestate from large biogas plants exceeds requirements of arable land. For example, a biogas plant of 500 kW capacity would require ca. 350 ha to keep within the nitrogen content and fertilizer regulation [42], but such areas of agricultural land are not always available. Therefore, the environmental regulations mean that, in most cases, the excess quantities must be transported over longer distances for disposal. Alternatively, the digestate may also be separated into liquid and solid fractions; the latter, approximately 40% [43] is subsequently transported, dried, incinerated for energy or sold as granular fertilizer, while the liquid fraction is pre-treated to drinking water quality. The drying process requires 13.6 kWh electric and 130 kWh thermal energy per tonne of digestate; translating to energy cost of €11.60/t. Separation of the digestate incurs energy costs of €1.05 or €0.06/t of digestate for decanter or screw-press technology, respectively. Fig. 5 shows that handling of reduced digestate flow rate after separation, e.g. for MSW can save energy costs up to 50% (€7.15–3.06/t) within a transportation distance of 30 km.

AD of feedstock such as liquid manure can reduce the methane and nitrous oxide emissions in digestate by up to 90% and 50%, respectively [44]. Secondary collection of residual gas from digestate in closed storage area could also be used to enhance biogas energy yield by ca. 10% [27] whereas energy demand for digestate handling strongly depends on treatment technology employed and the transportation distance (see Table 2 and Fig. 5).

4. Salient policy issues on potential for expanded utilization

Fuel extraction, energy utilization and transportation accounts for 80% of all GHG emissions in the European Union (EU) [45]. It is estimated that, with the current energy and transport policies in the region, CO_2 emissions will increase by 5% by 2030 and global emissions by 55% [46]; hence, the current energy policies are unsustainable. Also, it is estimated that EU's energy import dependence will increase from current 50% of total consumption, to 65% in 2030, of which the increased reliance on gas and oil imports will be the ranges of 57–84% and 82–93%, respectively. On the other hand, electricity demand in the EU is rising by 1.5% per year, which, even with an effective energy efficiency policy, presents a significant demand on investment in generation capacity for consumer prices to be competitive. However, it is recognised that, with right policies, the associated political and economic risks could be minimized to stimulate fair and competitive energy prices, energy savings, and higher investment in renewable energy technology in the EU energy market.

In December 2008, the European Parliament passed the Energy and Climate Change Package intended to reduce GHG emissions by 20% (compared to 1990 values) by the year 2020, increase utilization of renewable resources from currently 8.5% to 20%, and reduce energy consumption through improved energy efficiency [47]. The active Common Agricultural Policy [48] considers biogas as a mature technology that can contribute significantly to meeting targets for supply of renewable energy and mitigation of climate change [49]. It is arguable that, with successful implementation of compatible policies, the EU energy market can gain higher investment in renewable energy technology to minimise the dependency on energy imports.

Prospect for the expanded utilization of biogas in Germany is influenced by European policy strategies comprising: adopted strategies for decreasing import dependence and increasing security of energy supplies; cost competitiveness against other fuels, and; environmental goals (including relevance to integrated waste management system). At national level, the German government developed an integrated energy and climate program [50] for realisation of European policy strategies, which is one of

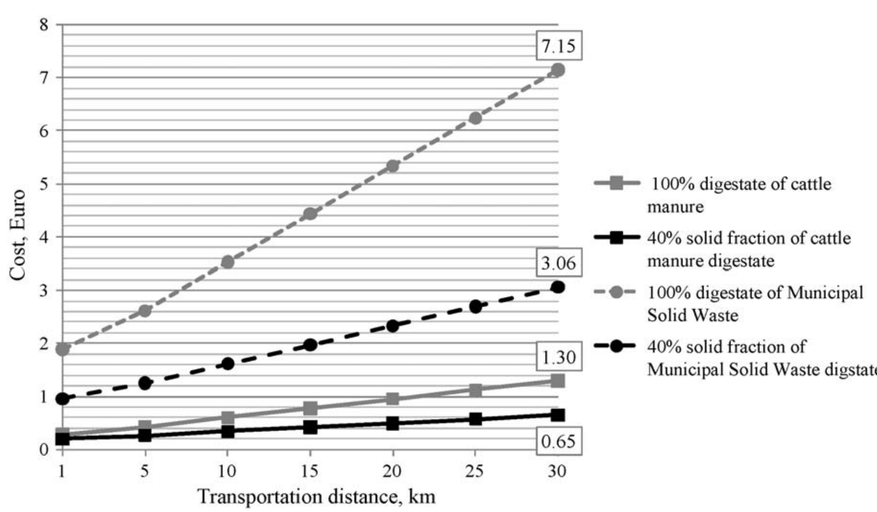

Fig. 5. Energy costs for loading, transport and spreading of digestate or solid fraction of digestate as function of transportation distance.

the most challenging worldwide [6]. The intention was to create framework for structured reduction of GHGs by 2020, in which 25–30% of electricity and 14% of heat will be generated from renewable resources. It is the contention of this study that, biogas technology can deliver a significant part of this requirement since the national program will provide easier access to the natural gas network for bio-methane, promote heat usage from renewable sources, and enhance regulations for renewables.

4.1. Implementation protocols for biogas plants

4.1.1. Location of biogas plants

The optimal location of biogas plants is affected by both regulations covering environmental protection and economic considerations. Environmental regulations prevent installation in nature reserves and water protection areas. Economic considerations include; existence of road infrastructure (including transportation costs for both feedstock and digestate; Table 2), existence of gas networks for bio-methane injection, and transmission efficiency limitations of district heating grids. Availability of adequate feedstock near the plant location significantly enhances efficiency of operation. For example, analysis of energy balance for transportation of corn silage and food residues was assessed to be negative for distances exceeding 350 and 90 km, respectively (Table 2).

Factors determining the local acceptance are associated with odour and noise levels [51], potential increase in traffic, and concerns on potential damage to landscape. If feedstock is predominantly energy crop, likely cultivation in monoculture which alter the natural sceneries and have negative impact on soil fertility are important considerations [52].

4.1.2. Regulations affecting biogas plant implementation

Permit for installation and operation of biogas plants is processed by the Federal Immission Control Act (BimSchG) which covers incineration facilities, digestion plants, and storage areas. The BimSchG covers waste disposal, treatment or storage, and includes legislation for handling of hazardous material, treatment of the digestate, and handling of animal by-products which may determine the optimal feedstock. Environmental impact assessment may also be necessary if the expected daily flow-rate of feedstock is high, and where preliminary examination declares potential environmental hazard. These act as barriers to implementation due to associated expenditure on consultancy.

Generally, the performance of a biogas plant will depend on the quality of installation, reliability of components used, and operator experience. In order to fulfil the minimum requirements for planning permission and safety standards, the feedstock delivery and digestate storage areas must be covered to eliminate odour emission. Noise pollution, e.g. from CHP generators must be minimised. Process emissions are minimised with airtight digesters and storage vessels, but outlet for unused gas is necessary for safety. Storage area for feedstock and digestate, as well as digesters must be leak-proof to protect ground water. For safety reasons, hazard points e.g. rotating machine elements, compressed gas lines or storage and locations with inherent danger of poisoning (feedstock, digestate, methane, and hydrogen sulphide) must be labelled, and protected or equipped with automated warning systems. These incur extra cost and can be a barrier to expanded utilization.

4.2. Incentives and barriers to biogas production

4.2.1. Economic support programs by the German government

The national target is to provide 12.5% of electricity from renewable resources by 2010, and up to 20% by 2020 [50]. To enable realisation of these targets, several support strategies have been implemented, and collectively should enhance prospects for expanded utilization of biogas. Fig. 6 shows comparative costs for electricity generation from fossil fuels and renewable sources. It is shown that electricity generation from renewable sources is more expensive and justifies the need for subsidy in the short term. Technology is the biggest uncertainty in the future of renewable energy; i.e., technology will continue to improve the economics and sustainability potential of biomass-to-energy chains.

4.2.1.1. Research, technology development and investment grants. Priority in the EU energy research and technology development theme is aimed at exploration of a wider mix of renewable energy resources. The drivers for this priority include, need for security of energy supply, energy efficiency improvement, and enhanced utilization of renewable resources. It covers innovation in biogas systems, including research on new feedstock, biogas technology and anaerobic process that will enhance efficiency of biogas production. Under an environment protection and energy saving program, low-interest loans directed to the protection of environment, soil, water and air, and utilization of renewable energy resources are available for small-scale biogas plants in Germany [53]. Large-scale biogas projects are often financed by power utility companies in collaboration with manufacturers of biogas production systems.

4.2.1.2. Subsidies. The Renewable Energies Act (EEG) is the most significant subsidy scheme for biogas plant operators. It guarantees payment for feed-in of electricity generation from biomass

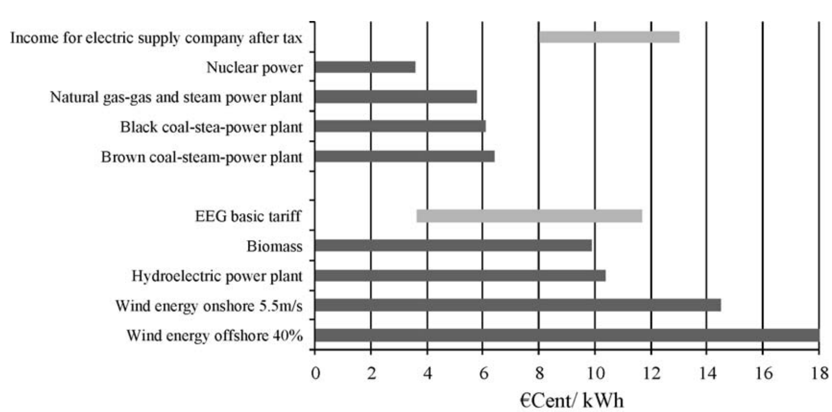

Fig. 6. Comparative cost for electricity generation from fossil fuels and renewable resource with consideration of different costs for emission allowances for new power plants (installation 2010). Light grey bars show income options from fossil energy for private households and industry sector as well as basic tariff for electricity from renewable energies within the EEG [88–90].

(excluding wood fuel) to the national grid over a period of 20 years. The payment is decreased by 1% annually, with the aim of encouraging plants to operate profitably, to gain gradual independence. The EEG provides additional payments for exclusive usage of renewable raw materials (RRM), co-generation of CHP, and technology innovations. The amended EEG effective from 2009 will only support biogas plants of up to 20 MW_{el}, as it is intended to discourage commissioning of large-scale centralised biogas plants; as opposed to small-scale decentralised units that promote rural development.

Biogas plants that also accept non-renewable feedstock do not qualify for RRM bonus therefore must operate more efficiently to remain competitive. A new bonus scheme will grant extra subsidy for biogas plants of up to 150 kW_{el} installed capacity and using a minimum of 30% by mass of liquid manure. This is an incentive for small-scale biogas plants to use liquid manure that is readily available with only requirement of transportation (Table 2).

The CHP bonus scheme for heat utilization outside of the plant is to encourage higher energy conversion efficiency, where energy output increases by approximately 40% compared to CHP without heat utilization (Table 1). The innovation or technology bonus is to encourage adoption of more efficient technologies, e.g. supports Fuel cell technology, deployment of Micro gas turbines, and production of bio-methane up to 5 MW_{el} equivalents. Data in Table 1 indicate the potential performance. Plants must deploy innovation and CHP generation capacity, or attain conversion efficiency greater than 45% to qualify for the bonus [54].

Table 3 shows the feed-in tariffs for electricity generation under the Renewable Energy Resource Act (EEG) and average costs per kWh_{el}. It is shown that the basic tariff in the EEG does not cover the unit cost of production at 80% operation efficiency of biogas plant. For biogas plants with installed generation capacity of up to 500 kW_{el} at least one criterion and from 500 kW_{el} capacity and higher even three criteria of the bonus scheme within the EEG must be fulfilled. Therefore biogas technology still relies on government subsidy to remain economically viable.

4.2.1.3. Tax reliefs. Biogas energy is exempt from energy tax when used with stationary plant, as an incentive for electricity generation. The tax relief compensates for the shortfall between the production costs and market prices for power [6]. Furthermore, the tax reform for vehicles in 2009 introduced a CO_2 tax for vehicles with exceeding limit values of CO_2 emissions. CO_2 and energy tax incentives for vehicles fuel have been discussed in Section 4.4. Such should encourage development of biogas as carbon free energy, among other competing renewable energy sources, in order to have the benefit of subsidized purchase to compete favourably with petroleum fuels; hence, they enhance the prospects for expanded utilization.

4.2.2. Waste management in the agricultural sector

Waste streams from animal production and field crop cultivation are popular feedstock for biogas plants. Under the European Hygiene (EU) Ordinance no. 1774/2002, liquid manure is defined as category 2 material (by-products with predictable risks), and can be used without pre-treatment [55]. Therefore, there are active incentives for use of agricultural waste as feedstock in biogas plants.

Although the regulation covering fertilizer application in agriculture sets the limits for nutrients application from digestate on farmland for protection of water, soil and the ecosystems, organic fertilizer is cheaper and more environmental sustainable [56]. Farmers are able to use standard agricultural machinery for spreading of treated digestate on farmland, but handling costs are high, estimated with €7–14/m^3 of the digestate [29]. Due to seasonal nature of application of liquid manure and requirement for the protection of water resources, up to six months of storage capacity is required for existing livestock; therefore, the investment on storage structures may be significant.

4.2.3. Production of energy crops

About 2 million ha of farmland in Germany is used to grow energy crops [18], and popular ones for biogas production include corn, sugar millet and grasses e.g. miscanthus (*miscanthus* × *giganteus*), ryegrass (*Lolium perenne*) and clover (*Trifolium*) [7]. All are covered by the EEG which is a key incentive for production. Due to the global grain shortage, there is no restriction on set-aside land [48], therefore, 1.6–2.9 million ha in the EU is expected to return to crop production. Corn grain is the preferred feedstock for biogas plants [57], and it can also be grown in most places, which is an added incentive, but energy costs for cultivation process (€1.87/t) are significant when compared to utilization of agricultural waste (Table 2). It has biogas yield of 450–700 m^3/t oDM [27]. However, unstable grain feedstock prices, exacerbated by competition for the limited land [52], i.e., versus food/fodder industries [6], has created uncertainties for biogas plants that use grain feedstock. Alternative biomass-to-energy conversion pathways (Fig. 7) also compete for energy crop feedstock based on efficiency and profitability [36]. Cross compliance requirements within the Common Agricultural Policy links direct payments to compliance with environmental, food safety, animal and plant health and animal welfare standards, and to the requirement to keep all farmland in good agricultural and environmental condition. This provides specific supports for cultivation of energy crops for biofuels for transportation and electricity and thermal energy generation from biomass feedstock, which can act as incentive for biogas production [48].

Harvest cycles for energy crops are short, which can limit biodiversity, and therefore is a major environmental disadvantage. On the other hand, energy crops have lower requirement for pesticides compared to most food crops, and therefore minimal impact on biodiversity [58]. The most potent barrier is having extensive areas under monoculture, which effects natural scenery and environment in different ways. Ley crops are the most attractive summer and winter catch-crop, due to their high yield [59]. Ongoing crop research aimed at optimisation of feedstock

Table 3
Feed-in tariffs for electricity generation under the Renewable Energy Resource Act (EEG) and average production costs per kWh_{el}.

Capacity, kW_{el}	Basic tariff, cents/kWh	Incremental tariff by bonus scheme, cents/kWh					Total cost per kWh_{el}[b]
		RRM[a]	CHP	Technology	Liquid Manure	Landscape work material/clean air	
≤150	11.67	7.0	2.0	3.0	4.0	2.0/2.0	17.46
150–500	9.46	7.0	2.0	3.0	1.0	1.0/1.0	15.85
500–5000	8.51	4.0	2.0	3.0	–	–	15.26
5000–20,000	8.03	4.0	3.0	–	–	–	14.5

Adopted from [95].

[a] Renewable raw materials.
[b] Assumed costs per unit for biogas plants with installed generation capacity of up to 500 kW_{el} and 80% operation efficiency.

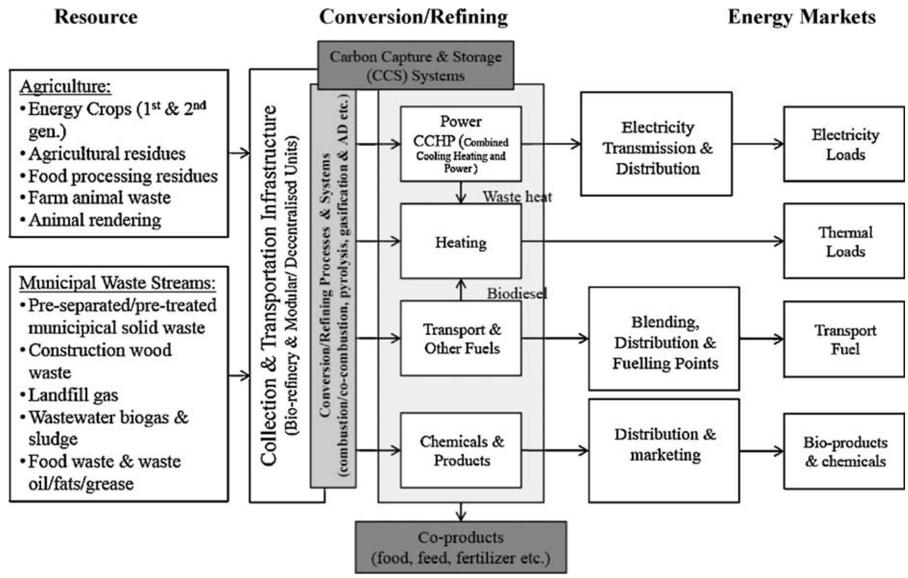

Fig. 7. Outlined of biomass-to-energy conversion pathways.

supply for biogas plants has identified Silphie (*Silphium perfoliatum*) [57] and Sudan Grass (*Sorghum sudanense*) [60] as possible alternatives to corn.

4.2.4. Industrial sector and municipal waste streams

Fig. 8 shows the proportions of industrial sector and municipal waste streams handled by different processing and disposal methods. Salient incentives and barriers to their utilization for biogas production are summarised in Table 4. Up to 1990, all organic waste was composted in open systems or disposed in landfills. By 2005, 88% was composted, half of which was in closed systems [61], the remaining 12% being treated by wet digestion process. Prognoses for stemming of climate change in the period up to 2020 estimates that up to 80% of organic waste will be treated by AD, and just 20% through the aerobic route [61].

The Federal Government's regulations on recycling and waste management and disposal of bio-wastes and sludge, focus on developing a closed cycle of matter designed to generate quasi zero-waste (Fig. 9) [62]. Energy production and recirculation of digestate through soil nutrients in closed CO_2 cycle provides scope for sustainable production, hence, expanded utilization of biogas. MSW is mainly disposed in landfills, but new policies (e.g. Environmentally Compatible Storage of Waste from Human Settlements and Biological Waste-Treatment Facilities [63]) restrict landfilling to control emissions and water pollution. Regulations governing disposal of bio-waste require safe disposal, without possible recirculation into the food chain through animal feeds [64]. Therefore, kitchen slop and residues from food industry are possible feedstock for biogas plants. However, EU regulations for non-human consumption of animal by-products [55], reinforced by the German regulation on disposal of animal by-products require pre-treatment (e.g., sterilization) of such feedstock, which incur handling costs and therefore potential barrier to expanded utilization (Table 2). Another barrier is the knowledge gap on co-digestion of food processing and MSW streams. It has been estimated that double the energy yield can be achieved by co-digestion of feedstock from industrial sector and MSW (16.4 GJ/t_{DM}) compared to feedstock from agricultural sector (8.9 GJ/t_{DM}) (Table 1). However, the differences in homogeneity, degradation and digestion times necessitate more R&D for optimal utilization. Furthermore, efficient and safe operation of biogas plants requires well trained personnel. Although it is generally accepted that the long-term benefits are higher, training is costly and therefore may be a barrier.

The national strategy is aimed at achieving zero MSW by 2020. A mix of waste treatment and energy recovery methods, besides AD is recommended. For example, currently there are 73 incineration plants with capacity for 17.2 million tonnes of waste [65], which compete for solid waste feedstock with biogas plants.

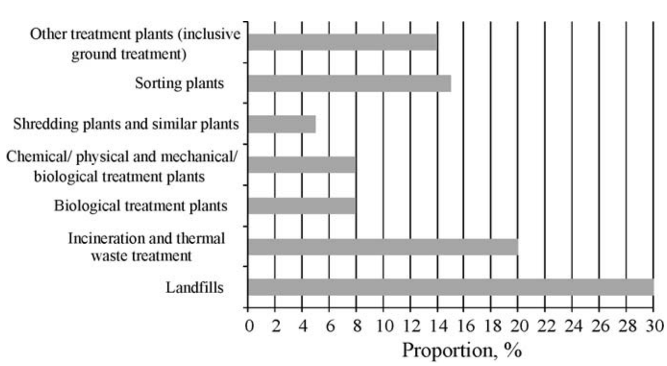

Fig. 8. Proportion of waste handled by different disposal methods used in Germany in 2005 [91].

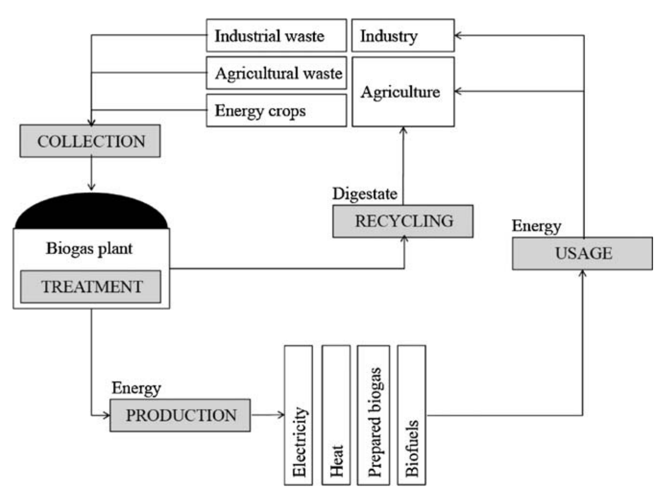

Fig. 9. Closed cycle of matter designed to generate quasi zero-waste.

Table 4
Summary of incentives and barriers to biogas production in Germany.

	Agricultural waste management	Energy crops	Industrial sector and municipal waste stream	Source
Incentives				
Legislation	Limits for nutrients per ha farmland	Common Agricultural Policy; specific supports for cultivation energy crops	Utilization reduction of municipal waste streams	[56,96,97]
	Water, ecosystem and soil protection		Restriction for landfilling of organic material Ban on feeding food waste and bone meal to animals	
Economy	Renewable Energies Act (EEG)[a,b] Tax reliefs for RE (energy tax) Tax on commercial fertilizer	Renewable Energies Act (EEG)[b] Tax reliefs for RE (energy tax) Cultivation all around Germany High energy yield	Renewable Energies Act (EEG)[c,d] Tax reliefs for RE (energy tax) Tax on fossil fraction for incineration plants Lower gate fees	[3,27,57]
Infrastructure/environment	Low emissions of GHG Reduction of odour Valuable fertilizer characteristics	Less pesticide compared to food cropping	Control of emissions and water pollution, closed cycle of matter therefore sustainable environment	[51,58,62–64]
Peer country comparison	Switzerland exceeds Germany in development of sustainable feedstock supply supported by tax reliefs but only for agricultural residue, as part of agricultural waste management. Switzerland, Sweden and Italy at par or inferior otherwise.			[83]
Barriers				
Legislation	Missing regulations for focused utilization of agricultural waste		Regulations about feedstock pre-treatment	[55,98]
Economy	High handling costs	High prices	Higher handling cost (pre-separation and pre-treatment) of waste	[36,52]
		Competing within available land Competing to alternative energy conversion	Investment costs for technology Knowledge gap on feedstock characteristics Competition with incineration and composting	
Infrastructure/environment		Limitation of biodiversity Extensive cultivation in monoculture		[58]
Peer country comparison	Switzerland exceeds Germany in sustainable production of energy crops supported just under socially compatible considerations. Switzerland, Sweden and Italy at par or inferior otherwise.			[83]

Structure adopted from [12].

a Liquid manure bonus.
b Renewable raw material bonus.
c CHP bonus.
d Innovation bonus.

However, incineration attracts energy tax on the fossil fraction used (Section 4.3). Also, biogas is classified as CO_2 neutral, i.e., approximately the same amount of CO_2 is released during combustion as was absorbed during growth of the biomass feedstock. On the other hand incineration plants emit significant quantities of CO_2 which incur extra costs for plants with more than 20 MW thermal capacity [66]. A lesser competitor is composting since some waste fractions must be pre-treated prior to composting, and it also incurs GHG emissions. A distinct advantage of AD is its ability to process liquid organic material, which is a more favourable feedstock for biogas production.

The waste management scenario in Germany has changed drastically since imposition of a ban on disposal of MSW to landfills [67]. Existing incinerators now work to full capacity and command high gate fees for waste, based on homogeneity and year-round availability of feedstock, quantity, handling requirement and technology at the waste treatment plant. Biogas plants rely on alternative feedstock from food processing and MSW streams, due to their easy availability, high gas yield (Table 1), and also high prices for alternative energy crop feedstock. High feedstock demand has led to reduction in gate fees (Table 5), therefore biogas plants are more attractive for management of organic waste [41].

Table 5
Gate fees for waste disposal in Germany [41,99].

		Gate fees, €/t
Incineration plant		60–350
Composting	Unpacked food waste	35–45
	Packed (expired food)[a]	75–95
Biogas plant	Municipal Solid Waste (MSW)	30–40
	Waste of industrial sector	25–30

a Includes pre-treatment costs for the composting process.

Table 6
Summary of incentives and barriers to biogas utilization in Germany.

	CHP	Heat generation	Gas grid injection	Vehicle fuel production	Source
Objectives	National targets for REL[c] (12.5%—2010, 20%—2020)	Target of 14% heat production from renewable sources by 2020	6 billion m^3 bio-methane by 2020	Biofuels Roadmap for replacement of fossil fuels	[6,50,53,79,100]
Incentives					
Legislation	Promotion of REL[c] (17.1%)	Market Incentive Program with grants and low-interest loans	Equal treatment of natural gas and biogas Preferred injection of biogas	Replacement of 4.4% diesel, 3.6% petrol by biofuels (2015)	[76,79]
Economy	Renewable Energy Act (EEG)[a] Energy tax reliefs	Renewable Energy Act (EEG)[a] Energy tax reliefs Generation of cooling energy Heating of digesters and nearby houses	Renewable Energy Act (EEG)[b] Energy tax reliefs Minimal transformation losses Benefits by GasNZV and GasNEV	Renewable Energy Act (EEG)[b] Energy tax reliefs Lower pump price for fossil fuel Highly competitive within RE[e]	[3,7,23,32,50,68,80]
Infrastructure/environment	Available electricity grid		Extension of gas network by regulations	Amenities offered by gas utility and insurance companies for acquisition of compressed gas vehicles	
Peer country comparison	Italy exceeds Germany in adoption of the Green Certificates System by coupling price for electricity generated from biogas and the value of green certificates. Switzerland and Sweden exceeds Germany in high tax exemptions for biogas. Switzerland exceeds Germany in enforcement of regulations for sustainable biofuel production, Swiss certification system "Naturmade Star" and mandatory payment scheme for methane gas feed-in. Switzerland, Sweden and Italy at par or inferior otherwise				[11,12,39,83–86]
Barriers					
Legislation	Low basic payment for electricity (EEG)	CHP bonus just for heat utilization outside			[3]
Economy	High prices for RRM[d] Higher price for "green electricity"	Competing fuels are cheaper High investment costs (storage) Complex technology Seasonal demand Limited demand for heat close-by	Natural gas is cheaper High investment cost (technology)	High production costs Higher pump price within RE[e] Higher purchase price for vehicles Competition with bio-ethanol	[7,32,74,75,101]
Infrastructure/environment		Availability of heat network	Availability of gas network	Marginal lower CO_2 saving within RE[e] Limited number of gas filling stations	[7]
Peer country comparison	Switzerland and Sweden exceed Germany in lowest price for biogas as transportation fuel and rapid expansion of infrastructure for natural gas grid and filling stations. Sweden exceeds Germany in economic incentives such as free parking and investment subsidies for cars fuelled by biogas. Switzerland, Sweden and Italy at par or inferior otherwise				[10–12]

Structure adopted from [12].

[a] CHP bonus.
[b] Innovation bonus.
[c] Renewable electricity.
[d] Renewable raw material.
[e] Renewable energy.

4.3. Incentives and barriers to biogas utilization

Energy tax is levied on the basis of the resource origin, i.e., if derived from fossil fuels or a renewable resource. Biogas does not attract energy tax, but other resources are charged as follows; heating oil 6.14, petrol 65.50, and diesel 47.04 cents/l, and €5.50/MWh on natural gas for CHP [68]. It is recognised that tax incentives alone will not meet environmental objectives; therefore, other policy instruments covering utilization have been developed. The EU Greenhouse Gas Emissions Trading System (EU ETS) in the National Environmental Policy is intended to meet targets in the Kyoto protocol. Emission trade focuses on energy utility and manufacturing sectors which account for 45% and 12.5% of the total CO_2 emissions, respectively [69]. Large power plants (>20 MW thermal capacity) and other energy intensive plants have prescribed maximum CO_2 emission allowance, but additional emission allowance can be purchased or reductions traded through a dedicated stock markets.

The current market price is approximately €20/t CO_2 [70] which could add value of approximately €8.3/MWh for energy supply from biogas (Fig. 1). Methane content in the digestate is also reduced by 95%, which could be a significant advantage in emission trading. The price of energy generation from fossil fuels and cost of CO_2 emission positively influences the potential for expanded biogas utilization. Whereas low price for energy from oil would lead to increased purchase prices for CO_2 emission allowances, high price for energy from oil could even lead directly to increased biogas utilization potential, among other competing renewable energy sources [71,72]. However, high fluctuating prices for CO_2 emission allowances (July 2008—€24/tCO_2; February 2009—€5/tCO_2) make the basis for sensitivity of biogas component unreliable [73]. Other policy instruments affecting utilization of biogas are summarised in Table 6, with the salient components discussed in Sections 4.3.1–4.3.4.

4.3.1. CHP generation

Besides tax relief and emission trade mechanisms previously outlined, the Renewable Energy Resource Act (EEG) favours biogas utilization for CHP (Table 3). The feed-in tariffs for generated electricity are guaranteed for 20 years with an annual reduction of 1% of the basic payment. Typical output of CHP generation from biogas is about 2/3 thermal and 1/3 electricity at 80–90% efficiency [7], which provides scope for enhancement of operational efficiency and therefore reduced cost with co-generation. For example, CHP without external heat utilization realizes just about 33% of energy in biogas (2.9 GJ/t_{DM}; Table 1), and plant efficiency may therefore be a barrier gaining subsidy-free operation. Electricity generated can also be sold to independent energy suppliers, on average at 2 cents/kWh higher than conventional supply [74]. However, there are no specific tax incentives for consumption of electricity from renewable resources.

4.3.2. Heat generation

Heat generation does not require refined fuels; therefore, competing amorphous fuels like fire-wood or wood chips determine the price-baseline. Domestic heat utility is still dominated by fossil fuels of which, in 2005, approximately 94.7% was generated from a mixture of natural gas, heating oil, electricity and coal (50.2%, 39.8%, 3.8% and 0.9%, respectively) and 5.3% of renewable resources. In the renewable fuels category, solid fuels account for 85% of heat generated, just 4% stems from gaseous fuels like biogas [75].

Presently, heating energy supplied from renewable resources is tax free, but natural gas is still the most popular heating fuel and costing €0.06/kWh compared to biogas at €0.07–0.18/kWh. Even for localised consumption, the unit heating cost is still at least €0.06/kWh [7]. There is a bonus for verifiable heat consumption from CHP plants. The Renewable Heat Energy regulation sets out heating concepts for buildings, provides financial support via a Market Incentive Program (MAP) [76] and the extension of the district heat network, which are all relevant to promotion of biogas technology. MAP's grants and low-interest loans that include discounts for heat utilization or CHP based on renewable resources. It is intended to minimise investment costs [6] and is therefore a strong incentive for small-scale biogas plants.

The seasonal demand for heat has to be considered in the planning process for biogas plants. For efficiency, exclusively production of heat is less attractive than CHP. The most common application of generated heat is to heating of digesters and the local residential houses and animal stalls, but other possible uses include heat transmission to public buildings, grain drying, production of animal feed, and drying of wood fuel [23]. This can increase the efficiency of biogas production by up to 40% in case of CHP with heat utilization (4.1 GJ/t_{DM}) compared to CHP without heat utilization (2.9 GJ/t_{DM}) (Table 1). Potential barrier to deployment of CHP for the use of heat component off-site is the high operating and investment costs for mobile heat storage. The estimated cost for portable heat storage is €0.07–0.32/kWh compared to €0.06/kWh heating cost based on oil boilers [77].

4.3.3. Gas grid injection

For economic reasons (Table 2), biogas plants are generally deployed at locations with feedstock resources, whereas, energy consumption is in locations with demand [32]. Therefore, bio-methane injection into the natural gas grid is the most efficient delivery system as conversion losses are avoided, hence, the entire energy in biogas can be used as substitute for natural gas (Table 1), to generate significant environmental benefits. Cost elements for bio-methane include: (i) biogas production cost of 3.5–8 cents/kWh depending on feedstock, plant size and volume flow of methane; (ii) preparation costs of 2–6 cents/kWh depending on gas flow rate, and; (iii) grid injection/conveyance fees of 0.3–2 cents/kWh depending on flow rate and transmission distance [7]. Comparatively lower cost of natural gas and high investment costs for bio-methane are key obstacles to expanded gas grid injection. Available data suggest that the break-even point for economic bio-methane production specifically for injection into the national grid is in the region of 1 MW at volumetric flow of at least 250 m^3/h [7] to more than 2 MW for 500 m^3/h [32], which can only be achieved by large-scale biogas plants.

Gas utility companies have raised concerns over the quality of bio-methane and therefore suitability for injection into natural gas grid [7], hence, the German Federation of Gas and Water Association prescribe minimum quality standards. The energy industry estimates that with increased gas grid access, 6 billion m^3 of bio-methane could be available for utilization as vehicle fuel and for CHP generation by 2020. However, the limited capacity of the gas grid may require preferential treatment of bio-methane. The regulation on access to natural gas network (GasNZV) benefits biogas producer by apportioning the injection cost to grid users and gas utility companies [50]. The regulation on payments for natural gas network (GasNEV) provides a relief of 0.7 cents/kWh for biogas due to shorter transmission distances for methane compared to natural gas [50]. Both regulations are aimed at offsetting the cost-intensive biogas production. Lately, there has been increased cooperation between utility companies like E.ON AG and biogas plant manufacturer such as Schmack Biogas AG in expansion of grid capacity.

4.3.4. Vehicle fuel production

Approximately 67,200 million litres of motor fuels were consumed in Germany in 2006, comprising 51.9% diesel, 41.8% petrol, 4.0% bio-diesel, 0.6% bio-ethanol, and 1.7% vegetable oil [78]. Present transport energy policies, e.g. the Biofuels Roadmap

Table 7
CO_2 and energy tax and prices for different vehicle fuels [78,80,102].

	Cost							
	Diesel	Petrol	Natural gas	Bio-methane[c]	Biodiesel	Bio-ethanol	Vegetable (rape oil)	Btl
CO_2 tax €/g CO_2 km[d]	2.00	2.00	0	0	0	0	0	0
Energy tax €/l	0.47	0.65	0	0	0.15 0.45[a]	0[b]	10.00 0.45[a]	0[b]
Pump price €/l	1.10–1.50	1.30–1.50	0.60 petrol 0.66 diesel	0.80–0.90	0.80–1.05	0.45–0.60	0.60–0.80	1.00–1.20

[a] Year 2012.
[b] Year 2015.
[c] €/kg.
[d] For exceeding of CO_2 emission limit for vehicles additional costs are regulated: 2010/11: 120 g CO_2; 2012/13: 110 g CO_2; 2013/14: 95 g CO_2.

[79], favour fossil fuel substitution, and therefore, increased utilization of renewable fuels such as bio-methane as they are deemed to be sustainable. Such policies are augmented by negligible transmission losses. The national biofuel policy targets the replacement of 4.4% diesel and 3.6% petrol with biofuels by 2015. Realisation of these targets can be enhanced by increased utilization of bio-methane.

Economic benefit of using bio-methane as transport fuel depends on cost competitiveness against petrol and diesel. Biofuels attract lower energy tax (Table 7) compared to diesel and petrol, and therefore have lower pump prices, which is an incentive for expanded utilization of bio-methane [80]. However, within the biofuel range, bio-methane is most expensive, despite being the most competitive in respect to fossil fuel equivalence and attainable travel distance per ha of primary resource production (Table 8). The saving in CO_2 emission is marginally lower. Production cost for bio-methane is at par with other biofuels, but the current pump price for CNG (5.35 cents/kWh), can only be matched by cost of bio-methane from large plants (5.8 cents/kWh) with flow rate of at least 500 m^3/h [7].

There is parity in cost for CNG and diesel passenger cars. Adaptation of petrol vehicles for CNG costs between €2000 and €3500. Currently, some insurance firms associated with the main gas utility companies provide discounted premiums for biofuel vehicles. Also, some gas utility companies offer refuelling coupons as incentives for gas vehicles. Vehicles powered on bio-ethanol are marginally cheaper than those adapted for bio-methane/CNG. However, since the origin of the bio-ethanol sold in Germany is mostly from lesser developed countries [81] with conflicting land-use policies, this supply is unsustainable [82], therefore there is compelling case for gas vehicles. The limited infrastructure of filling stations remains a barrier to expanded use of bio-methane as transportation fuel.

4.4. Best practice benchmarking against biogas peer group of countries in the EU

Best practice benchmarking in the context of this paper is a means of evaluating the various aspects of integrated feedstock-to-biogas production chain, including biogas utilization options and disposal of spent-feedstock—the digestate, in relation to best practice elsewhere. It is considered as a continuous process by which Germany can seek to challenge its technology and practice towards technically and economically viable and environmentally efficient, and therefore sustainable production and utilization of biogas. In this study, benchmarking was against three biogas peer group of countries that are known for pioneering different aspect of biogas production (Table 4) and utilization (Table 6). Their selection criteria were discussed in Section 1.

With almost 4000 installed biogas plants, and more than 500 manufacturers with 10,000 employees in the biogas branch, Germany is one of the most experienced countries in biogas technology in the EU. The fixed feed-in-tariffs for electricity sold to the national grid within the EEG is main driving force for fast expansion of renewable energy resources. However, it is arguable that high feed-in-tariffs for electricity generation alone could lead to neglect of (i) overall operational efficiency by e.g. heat utilization and (ii) environmental impacts by e.g. sustainable feedstock logistics. For expanded utilization, parity assessment against best practice in peer countries provides scope for enhancing utilization.

Expansion of biogas plants in Switzerland did not happen as fast as in Germany, because the initial focus was on development of sustainable feedstock supply supported by tax reliefs just for residues of agriculture and production of feedstock e.g. energy crops under socially compatible considerations [83]. Biogas utilization as a fuel enjoys tax exemption, but the associated GHG emissions must be at least 40% lower compared to fossil fuels, and energy- and emission balances have to be positive. Exemption from fuel tax when biogas is used as transportation fuel makes biogas the lowest priced of all fuels at filling stations [10]. In the period 2005–2008, filling station infrastructure for natural gas and bio-methane realized over 70% expansion, i.e., from 60 to approximately 100 filling stations [39]. There is no mandatory payment scheme for methane gas feed-in, but the association for the Swiss gas industry VSG has signed an agreement with biogas association to pay a premium price for the feed-in of biogas. The Swiss certification system "Naturmade Star" guarantees sustain-

Table 8
Comparison of biofuels [78,80].

Vehicle fuel	Fuel equivalent (l) (diesel, petrol = 1)	Distance (km/ha resource)	CO_2 savings (kg/l biofuel)	Production costs in average (€/l)
Bio-methane	1.4[b]	67,600	1.15/kg	1.04[d]
Bio diesel	0.91	23,300–40,900	2.20	0.63
Bio ethanol	0.65	22,400–36,800[c]	1.15–2.40[c]	0.22–0.64[c]
Vegetable oil (rape oil)	0.96	23,300–40,900	2.20	0.49
Btl[a]	0.97	64,000	2.53	1.00

[a] Biomass-to-liquid.
[b] Bio-methane in (kg), made from corn silage.
[c] Depends on feedstock used.
[d] €/kg.

ability through compliance with environmental, process and social criteria for biogas production [83]. In contrast to Germany, the expansion of biogas technology in Switzerland has been driven by technological innovations rather than availability of subsidy per se [10]. Since technology is the biggest uncertainty in the future of renewable energy, i.e., technology will continue to improve the economics of bioenergy development, such a model may be more realistic basis for sustainable biogas utilization.

The major part of the biogas produced in Sweden is used for heating, but increasing share is upgraded and used as a vehicle fuel or injected to the gas grid [39]. Biogas production for vehicle fuel increased from 3 TJ in 1996 to more than 1000 TJ in 2006 and accounts for 24% of total biogas production [12,84]. Today there are 12,000 vehicles using upgraded biogas/natural gas, and it is forecasted that there will be 70,000 vehicles and 500 filling stations by 2010 [85]. Successful proliferation of biogas in transportation sector is attributed to several factors, including economic incentives such as CO_2 tax exemptions [85], government investment programs for extension of the natural gas grid, green gas principle allowing for upgraded biogas access to natural gas grid [84], and free parking and investment subsidies for cars fuelled by biogas [12]. Thus, the current market price for bio-methane is 20–30% lower than petrol on energy basis [11]. Existing incentives and support infrastructure for biogas utilization in Sweden exceeds Germany (Table 6).

In Italy, biogas plants have short amortization periods (typically 4–7 years), because of the adopted Green Certificates System. Payments for feeding electricity from biogas production constitute price for electricity production (€80–95/MWh) and the value of green certificates (€125/MWh) [11,86]. The tradable Green Certificates System [85] could enable subsidy-free operation in the long term.

From the best practice benchmarking, the selected peer countries exceed Germany in the following key area of the process chains:

(1) Biogas production in Switzerland is based on sustainable feedstock supply, primarily agricultural residues. Sustainable feedstock supply is key to expanded utilization of biogas (Table 2).
(2) Biogas utilization in Italy is enhanced by the Green Certificates Scheme by coupling price for electricity generated from biogas and the value of green certificates. This scheme focuses on minimising barriers in production costs per kWh_{el} compared to income options for generated energy from biogas production, thereby gaining gradual progression to lower subsidy and possibly future subsidy-free operation. This is yet to be achieved in Germany (Table 3). Switzerland exceeds Germany in enforcement of regulations for sustainable biofuel production and implementation of a mandatory feed-in tariff scheme for bio-methane, which is the most promising biogas utilization pathway (Table 1). Switzerland and Sweden exceed Germany in lowest price for biogas used for transportation fuel compared to pump prices in Germany (Table 7) and in the robust infrastructure of natural gas grid and filling stations.

5. Conclusions and recommendations

Biogas technology could make a significant contribution towards meeting the national targets for renewable energy deployment in Germany, but only about 10% of the total technical potential is currently utilized. This suggests that existing technology and policy drivers and the accompanying incentives need to be enhanced. Although the range of government supported investment grants and subsidies provided under the Renewable Energies Act (EEG) and energy tax reliefs are available, significant barriers to expanded utilization exist in the entire process chain from feedstock optimisation, through biogas plant implementation, to AD process management and in the biogas utilization phases.

Sustainable feedstock supply which considers operational efficiency, minimisation of environmental impacts, and socio economic issues such as utilization of locally available resources and job creation is central to expanded utilization of biogas. Industrial waste streams can gain higher biogas yield than agricultural feedstock (i.e., 5.9 GJ/t_{DM} versus 12.7 GJ/t_{DM} for cattle manure and food residues, respectively). However, higher energy costs associated with feedstock pre-treatment and sterilization (mandatory for industrial waste streams), and the collection and transport of food residue feedstock are higher than those associated with agricultural waste such as cattle manure which only bears transportation cost. Considering the fluctuation in type and availability of feedstock, it is important to secure long-term feedstock supply as may be practicable.

Energy crops and agricultural residue feedstock in co-digestion generate environmentally safe digestate disposal. On the other hand, the use of organic waste from agri-food industry and MSW allow for integrated waste management with energy generation, while also attracting gate fees. Fluctuating feedstock availability (e.g. for agricultural residue) and pricing (e.g. for energy crops), and potential impacts of land-use changes on food crops require focused R&D to develop wider feedstock range, especially for AD process in co-digestion. It was shown that co-digestion of feedstock from industrial sector and MSW, can yield up to double energy output (16.4 GJ/t_{DM}) of co-digestion of feedstock from agricultural sector (8.9 GJ/t_{DM}). Environmental incentives include the potential reduction of GHG, and available data estimates the specific CO_2 reduction from utilization of biogas at €8.3/MWh, and biogas is the only renewable energy source with net reduction in CO_2 emission.

In Germany, biogas is mainly used for electricity generation and feed-in to the national grid, where the related subsidies provide incentive for expanded utilization. However, unstable feedstock costs combined with decreasing feed-in tariffs have negative implications. Development of renewable electricity utility market through enactment of CO_2 tax on fuels and implementation of "green gas" certificates to foster production cost parity with fossil fuels could stimulate expanded utilization, hence, gradual subsidy-free biogas plant operation. Italy has a successful example, where feed-in tariffs partly compensates for electricity production at €80–95/MWh and is augmented by €125/MWh green certificates for biogas.

In view of the success in peer countries identified and the inherent utilization technology options covered in this study, the upgrade of biogas to natural gas quality for injection into gas grid and utilization in the transportation sector are arguably the most energy efficient utilization pathways that could support rapid utilization expansion. Lower transmission losses, possibility for transmission to expansive market and decentralised production (closer to feedstock source to minimise transportation cost) supports this view. It was found that system energy balance turns negative for transportation distances exceeding 22, 350 and 425 km for cattle manure, corn silage and MSW, respectively. Whereas technical capacity is available for such deployment, investment costs are still high, and only economic for large-scale plants. For example the break-even point for gas upgrade technology for subsequent injection into the national grid is ca. 1–1.5 MW_{el}, which restricts deployment to large-scale plants. More robust electricity and gas grid infrastructure for easier access by biogas plants is required to enhance expanded utilization and flexibility for plant location.

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References

[1] AEE. Biogas in Germany 1992-2009: number of biogas plants in Germany and installed electrical power in MW. Renewable Energies Agency; 2009, http://www.unendlich-viel-energie.de/.
[2] BMU. Renewable Energy Sources Act (EEG). Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2004. http://www.bmu.de/.
[3] BMU. Act Revising the Legislation on Renewable Energy Sources in the Electricity Sector and Amending Related Provisions—Renewable Energy Sources Act (EEG) 2009, Federal Law Gazette 2008 I No. 49 of 25 October 2008. Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2009. http://www.bmu.de/english/renewable_energy/downloads/doc/42934.php.
[4] AEE. Biogas: data and facts 2008. Renewable Energies Agency; 2008. http://www.unedlich-viel-energie.de/.
[5] Kaltschmitt M, Scholwin F, Hofmann F, Plättner A, Kalies M, Lulies S, et al. Analysis and evaluation of possibilities for biomass. Wuppertal Institute for Climate, Environment and Energy; 2005, http://www.wupperinst.org/.
[6] Faulstich M, Greiff K. Biogas—a sustainable contribution to energy supply? Results of a special survey of German Council of Environmental Advisors (SRU)In: 17th annual convention of German Biogas Association. Germany: Congress Centre Nuremberg, German Biogas Association; 2007. p. 77–92.
[7] FNR. Feeding biogas into gas network. Agency for Renewable Resources; 2006 , http://www.fnr.de/.
[8] Scholwin F. Which biogas plant is the right one?. Institute for Energy and Environment; 2007, http://www.ie-leipzig.de/.
[9] FvB. Figures of the biogas branch 2007. German Biogas Association; 2008, http://www.biogas.org/.
[10] Markard J, Stadelmann M, Truffer B. Prospective analysis of technological innovation systems: identifying technological and organizational development options for biogas in Switzerland. Research Policy 2009;38(4):655–67.
[11] Tricase C, Lombardi M. State of the art and prospects of Italian biogas production from animal sewage: technical-economic considerations. Renewable Energy 2008;34(3):477–85.
[12] Lantz M, Svensson M, Björnsson L, Börjesson P. The prospects for an expansion of biogas systems in Sweden—incentives, barriers and potentials. Energy Policy 2007;35(3):1830–43.
[13] Börjesson P, Mattiasson B. Biogas as a resource-efficient vehicle fuel. Trends in Biotechnology 2008;26(1):7–13.
[14] Edelmann W. Biogas production and usage. In: Kaltschmitt M, Hartmann H, editors. Energy from biomass: basic principles, technologies and processes. Leipzig, Germany: Springer; 2001.
[15] Görisch U, Helm M. Biogas plants, first ed., Stuttgart, Germany: Ulmer; 2006.
[16] FAL. Results of the biogas program of measurements. Federal Agricultural Research Centre; 2005.
[17] Paterson M. Biogas in Germany—an overview. In: naro.tech—exhibition on renewable resources. Erfurt, Germany: Agency for Renewable Resources; 2007
[18] FNR. Data and facts to renewable resources. Agency for Renewable Resources; 2007.
[19] FNR. Biogas—an introduction. Agency for Renewable Resources; 2008.
[20] Grübler A, Nakicenovic N, Victor DG. Dynamics of energy technologies and global change. Energy Policy 1999;27(5):247–89.
[21] Brennan L, Owende PMO. Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and Sustainable Energy Reviews 2010;14(2):557–77.
[22] FvB. Influences of efficiency in crop cultivation on discussion for biogas potential. German Biogas Association; 2006, http://www.biogas.org/.
[23] Aschmann V, Effenberger M, Gronauer A, Kaiser F, Kissel R, Mitterleitner H, et al. Basic principles and technology. In: Bavarian Regional Authorities for Environment (LfU), editor. Bavarian biogas guideline—material volume, Augsburg, Germany; 2007.
[24] FNR. Biogas—basic data of Germany. Agency for Renewable Resources; 2008, http://www.fnr.de/.
[25] BMU. Material flow analysis for sustainable utilization of biomass. Cooperative project of Federal Ministry for the Environment Nature, Conservation and Nuclear Safety. Final Report; 2004.
[26] FNR. Cultivation of renewable raw material in Germany. Agency for Renewable Resources; 2008, http://www.fnr.de/.
[27] FNR. Guidance—biogas production and utilization. Agency for Renewable Resources; 2006, http://www.fnr.de/.
[28] Mitterleitner H, Schilchner A, Demmel M. Concepts for cost reduction of transportation renewable resources for biogas plants. Bavarian Regional Authorities for Agriculture (LfL); 2007.
[29] KTBL. Empirical values for biogas, first ed., Darmstadt, Germany: The Association for Technology and Structures in Agriculture; 2007.
[30] Thoss C, Schöne F. Biogas with prospect of ecology and nature conservation. German Association for Landcare (DVL) and German Society for Nature Conservation (NABU); 2008, http://www.landschaftspflegeverband.de/.
[31] Fischer T, Krieg A, Chae KJ, Yim SK, Choi KH, Park WK, et al. Farm-scale biogas plants. Journal of the Korean Organic Waste Recycling Council 2002;9(4):136–44.
[32] Helm M. Factors of efficiency within gas injection. In: Experts seminar: risks with biogas plants from point of efficiency, legislation and biological process. Nuremberg, Germany: Cooperation of consultants for biogas; 2008.
[33] Scholwin F, Thrän D, Daniel J, Weber M, Fischer E, Jahraus B, et al. Monitoring of consequences from the amended Renewable Energy Sources Act (EEG) to the development of power generation from biomass. Institute for Energy and Environment; 2007, http://www.ie-leipzig.de/.
[34] Gottschick M. Biogas—income alternative for farmers? Germanwatch e.V.; 2006. http://www.germanwatch.org/.
[35] Vogtherr J, Oechsner H. Gas-proof closing of final storage. Biogas Journal 2008;1/08(1):40–3.
[36] Kaltschmitt M, Hartmann H. Energy from biomass—basic principles, technology and processes, first ed., Berlin, Germany: Springer; 2001.
[37] Trogisch S, Baaske W. Biogas powered fuel cells, first ed., Linz, Austria: Trauner; 2004.
[38] Scholwin F. State of the art for biogas treatment for feeding into the natural gas network in Germany. In: 17th Annual Convention of German Biogas Association. Germany: Congress Centre Nuremberg, Institute for Energy and Environment; 2008. p. 169–81.
[39] Wellinger A. Biogas Upgrading and bio-methane usage in Switzerland. in 6. Hanauer Dialog—Biogas Upgrading to Bio-methane. Pliening, Germany: Institut für Solare Energieversorgungstechnik Verein an der Universität Kassel e. V. (ISET); Fachagentur für Nachwachsende Rohstoffe (FNR); The Federal Ministry of Food, Agriculture and Consumer Protection (BMELV); 2008, p. 54–71.
[40] Hillman KM, Sanden BA. Exploring technology paths: the development of alternative transport fuels in Sweden 2007–2020. Technological Forecasting and Social Change 2008;75(8):1279–302.
[41] 15th International Trade Fair for Water-Sewage-Refuse-Recycling (IFAT). Fuel cells for biogas plants and gate fees for waste disposal in Germany. Personal communication; 2008.
[42] Pietzsch K, Köttner M. Pre-treatment of digestate—aims, methods, costs. in 6. Rottaler Biomasse Fachgespräche: Biomasse—Kostenfaktor Nr. 1 in der Biogasanlage. Rottersdorf, Germany: Internatioanl biogas and bioenergy competence centre (IBBK); 2007.
[43] Döhler H. Methods and costs for fermentation residue treatment. In: 17th Annual Convention of German Biogas Association. Germany: Congress Centre Nuremberg, German Biogas Association; 2007. p. 151–8.
[44] Sommer SG, Petersen SO, Moller HB. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutrient Cycling in Agroecosystems 2004;69(2):143–54.
[45] EEA. Indicator: EN01 Energy and non energy-related greenhouse gas emissions (2007.04). European Environment Agency; 2008. http://themes.eea.europa.eu/Sectors_and_activities/energy/indicators/EN01,2007.04.
[46] EC. An Energy Policy for Europe. European Community Directive: COM (2007) 1 Final; 2007. p. 27.
[47] EC. Climate change and energy package 20 20 20 by 2020. European Community Directive; 2008.
[48] EC. Council Regulation (EC) No 1107/2007 of 26 September 2007 derogating from Regulation (EC) No 1782/2003 establishing common rules for direct support schemes under the common agricultural policy and establishing certain support schemes for farmers, as regards set-aside for the year 2008. Official Journal of the European Union 2007, http://eur-lex.europa.eu/JOHtml.do?uri=OJ:L:2007:253:SOM:EN:HTML.
[49] Pilzecker A. Biogas in the New Common Agricultural Policy. In: AEBIOM workshop: biogas—a promising renewable energy source for Europe; 2008.
[50] BMU. The Integrated Energy and Climate Programme of the German Government. Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2007, http://www.bmu.de/english/climate/downloads/doc/print/40589.php.
[51] Einfeldt D. For good neighbourhood: with less noise and odour you will get more acceptances. In: 15th Annual Convention of German Biogas Association. Germany: Convention Centre Hannover, German Biogas Association; 2006 p. 185–99.
[52] Heck P. Renewable Resources as option for environmental protection. In: Symposium energy crops. Berlin, Germany: Agency for Renewable Resources; 2007. p. 171–82.
[53] KfW. Environment protection and energy saving programme. Kreditanstalt für Wiederaufbau; 2008. http://www.kfw-foerderbank.de/.
[54] FvB. Questions and answers for practical application of the readjusted law for renewable energies within power generation. German Biogas Association; 2006, http://www.biogas.org/.
[55] EC. Regulation (EC) No. 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption. European Commission: Official Journal L 273 10/10/2002; 2002.
[56] BMELV. Regulation covering fertilizer application (DüV). Federal Ministry of Food Agriculture and Consumer Protection; 2007, http://bundesanzeiger.de/.
[57] Vetter A, Nehring A, Conrad M. Alternatives to corn—what can they achieve?In: 17th Annual Convention of German Biogas Association. Ger-

many: Congress Centre Nuremberg, German Biogas Association; 2007 . p. 101–8.
[58] Hufnagel J. Ecological concomitant research for energy crop production. In: Symposium energy crops. Berlin, Germany: Agency for Renewable Resources; 2007. p. 151–62.
[59] Benke M. Agricultural grasslands as biogas feedstock. In: Symposium energy crops. Berlin, Germany: Agency for Renewable Resources; 2007. p. 97–112.
[60] Kuhlmann F, Toews T. Economical evaluation of different cropping systems. In: Symposium Energy crops. Berlin, Germany: Agency for Renewable Resources; 2007. p. 225–40.
[61] BMU. Status report as contribution of the management to climate protection and possible potentials. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 205 33 314 UBA-FB III; 2005.
[62] BMU. Act for promoting closed substance cycle waste management and ensuring environmentally compatible waste disposal (KrW-/AbfG). Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2006, http://www.bmu.de/.
[63] BMU. Ordinance on environmentally compatible storage of waste from human settlements and on biological waste-treatment facilities (AbfAblV). Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2001, http://www.bmu.de/.
[64] BMU. Ordinance on the utilization of biowastes on land used for agricultural, silvicultural and horticultural purposes (ordinance on biowastes—BioAbfV). Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 1998.
[65] FEA. Plants for thermal waste treatment. Federal Environmental Agency; 2008, http://www.umweltbundesamt-umwelt-deutschland.de/.
[66] DeHSt. Application areas for the Greenhouse Gas Emission Trading Act for the allocation periode 2008–2012. The German Emissions Trading Authority (DEHSt) at the Federal Environment Agency; 2008. http://www.dehst.de/cln_099/nn_476596/SharedDocs/Downloads/Publikationen/Anwendungsbereich__TEHG__2008-2012.html.
[67] Saft RJ, Elsinga W. Source separation, composting a win for greenhouse gas reduction. Biocycle. Journal of Composting & Organics Recycling 2006;47(8):50–3.
[68] StaBA. Data of energy price development. Federal Statistical Office; 2008, http://www-ec.destatis.de/.
[69] FEA. Energy-induced emissions from 1990 until 2006. Federal Environmental Agency; 2007, http://www.umweltbundesamt.de/.
[70] Anonymous. Market information about prices for emission allowance. CO_2 Handel.de; 2008. http://www.co2-handel.de/.
[71] Redl C, Haas R, Keseric N. Price formation in liberalized markets for electricity with specific consideration of emissions trading. Vienna University of Technology, Energy Economics Group; 2006, http://www.eeg.tuwien.ac.at/.
[72] Sijm JPM, Bakker SJA, Chem Y, Harmsen HW, Lise W. CO_2 price dynamics: the implications of EU emissions trading for the price of electricity. Energy Research Centre of the Netherlands; 2005, ECN-C-05-081.
[73] EEX. Emission futures chart. European Energy Exchange; 2009 , http://www.eex.com/.
[74] Wagner E. Rates for ecological power: What are they, what do they effect? Energie-Fakten.de; 2008. http://www.energie-fakten.de/.
[75] FEA. Provide resources efficient and sustainable. Federal Environment Agency; 2007, http://www.umweltbundesamt-umwelt-deutschland.de/.
[76] BMU. Market incentive programme for renewable energies (MAP). Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2009, http://www.bmu.de/.
[77] Zielbauer J, Gaida R, Knott G. Heat utilization of biogas plants. Saxon State Ministry of the Environment and Agriculture, Journal series 17; 2007.
[78] FNR. Biofuels—basis data. Agency for Renewable Resources; 2008 , http://www.fnr.de/.
[79] BMU. Joint strategy. Biofuels roadmap. Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2007.
[80] FNR. Biofuels—a comparative analysis. Agency for Renewable Resources; 2006. http://www.fnr.de/.
[81] Junginger M, Bolkensjo T, Bradley D, Dolzan P, Faaij A, Heinimö J, et al. Developments in international bioenergy trade. Biomass and Bioenergy 2008;32(8):717–29.
[82] Peters J, Thielmann S. Promoting biofuels: implications for developing countries. Energy Policy 2008;36(4):1538–44.
[83] Wellinger A. Certification of bio-methane as basis for international trading. In: 18th Annual Convention of German Biogas Association. Germany: Exhibition Centre Hannover, German Biogas Association; 2009. p. 139–45.
[84] Dahlgren S. Biogas state of the art—Sweden. In: AEBIOM workshop: Biogas—a promising renewable energy source for Europe; 2008.
[85] SEA. The electricity certificate system 2008. Swedish Energy Agency; 2008, http://www.swedishenergyagency.se/.
[86] Piccinini S. The case of Italy. In: AEBIOM workshop: Biogas—a promising renewable energy source for Europe; 2008.
[87] Fritsche U. Greenhouse gas emissions and abatement costs of nuclear, fossil and renewable power production. Öko-Institut e.V; 2007.
[88] BMFT. Energymix. 2008. http://www.energie-verstehen.de/.
[89] BMFT. Development of energy prices und price indices—Germany; 2009.
[90] VdEW. Electricity prices in Germany. Verband der Elektrizitätswirtschaft Baden-Württemberg e.V.; 2008. http://www.vfew-bw.de/.
[91] StaBa. Environment waste disposal. Federal Statistical Office; 2007, http://www-ec.destatis.de/.
[92] Wiljan H. Guided tour to biogas plant Kirchstockach/Brunnthal digesting Municipal Solid Waste and food residues of city Munich. Personal communication; 2009.
[93] Goerten J, Ganea DC. Electricity prices for second semester 2008. eurostat; 2009. http://epp.eurostat.ec.europa.eu/.
[94] StaBa. Average price for diesel from May 2008 until August 2009 in cent per litre. Federal Statistical Office; 2009, http://de.statista.com/.
[95] Walla C, Schneeberger W. The optimal size for biogas plants. Biomass and Bioenergy 2008;32(6):551–7.
[96] BMU. Federal soil protection act and ordinance. Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 1998.
[97] BMU. Ordinance on Landfills and Long-Term Storage Facilities and Amending the Ordinance on Environmentally Compatible Storage of Waste from Human Settlements and Biological Waste-Treatment Facilities from 24 July 2002 (BGBl. I p. 2807), last changed by article 2 of regulation from 13 December 2006 (BGBl. I p. 2860). Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2002.
[98] EC. Green paper—on market-based instruments for environment and related policy purposes. European Community Directive: COM (2007) 140 final; 2007.
[99] Mathews W. Gate fees for waste treatment in Germany. Personal communication; 2008.
[100] BMU. An overview to The Renewable Energies Heat Act. Federal Ministry for the Environment Nature Conservation and Nuclear Safety; 2008.
[101] Reuß M. Seasonal storage of heat underground—is it an efficient solution for heat utilization of biogas? The Bavarian Centre for Applied Energy Research (ZAE) 2001.
[102] Anon. The natural gas vehicle—save money by low fuel price; 2008. http://www.erdgasfahrzeuge.de/preisvergleich.html.

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